Measuring strangeness in the nucleon*

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ABSTRACT. Evidence for strangeness matrix-elements in the proton are reviewed and other measurements for specific strangeness matrix elements are presented.

RESUMEN. Se hace una revisión de la evidencia de elementos de matriz de extrañeza en el protón. Se presentan también otras mediciones de ciertos elementos de matriz de extrañeza específicos.

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1. INTRODUCTION. EVIDENCE FOR STRANGENESS

It is generally believed that, at lower energies, the quark structure of the nucleon is given by three valence quarks, u u (up) d (down) for the proton and d d u for the neutron. However, surprisingly, some recent experiments indicate the presence of appreciable ($\sim 20\%$) strangeness. I will review the major pieces of evidence.

1.1. *The σ-term in π-N scattering*

The π-N σ-term is a measure of chiral symmetry violation. It is generally agreed that this violation arises primarily, if not solely, from the non-vanishing masses of the (current) quarks. The term measures the change of the mass of the nucleon when the masses of the quarks are "turned on"

$$\sigma_{\pi N} = \sum_q m_q \frac{\partial M}{\partial m_q} \approx \langle N| m(\bar{u}u + \bar{d}d) + m_s(\bar{s}s)|N\rangle. \tag{1}$$

The effect can be calculated with PCAC (partial conservation of the axial current) and some weak quark model assumption [1]. Experimentally [2], it is obtained from an extrapolation of low energy pion-nucleon scattering data to the non-physical Cheng-Dashen point [3] ($q^2 = 2m_\pi^2$):

$$\sigma_{\pi N}(2m_\pi^2) = \sigma_{\pi N}(0) - \frac{3}{8\pi}\frac{g_A^2}{4}\frac{m_\pi^2}{f_\pi^2}, \tag{2}$$

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where g_A is the weak axial vector coupling constant, m_π is the pion mass, and f_π is the weak pion decay constant. A recent re-analysis of the data [4] has narrowed the discrepancy between theory and experiment:

$$\sigma(\exp) \approx 45 \pm 5 \text{ MeV},$$
$$\sigma(\text{th}) \approx 25 \text{ MeV}. \tag{3}$$

The discrepancy can be understood in a number of ways. One of the most straightforward ones is to assume that $\langle N|\bar{s}s|N\rangle$, the scalar strangeness matrix elements of the proton, is of the order of 15% of $\langle N|\bar{u}u + \bar{d}d + \bar{s}s|N\rangle$.

1.2. The spin-structure of the proton

Recent measurements by the European Muon Collaboration (EMC) of polarized muon scattering [5] on polarized protons allow one to obtain the spin structure function of the proton. The experiment is thus sensitive to the strangeness axial-vector matrix element $\langle p|\bar{s}\gamma^\mu\gamma^5 s|p\rangle \approx \langle p|\bar{s}\vec{\sigma}s|p\rangle$. The measurement allows one to obtain the asymmetry

$$a = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}, \tag{4}$$

where σ_+ is the cross section for electrons polarized parallel to the spin of the proton (p) and σ_- is that for electrons polarized antiparallel to the proton's spin. The asymmetry, a, allows one to deduce the polarized structure function $g_1(x)$, where $x = q^2/2M\nu$, with $(\nu, \vec{q})$ the components of the four-momentum transfer q, and M the mass of the nucleon. In the infinite momentum frame, x can be interpreted as the Bjorken scaling variable $x = p_q/p$, with p_q the momentum of a quark and p that of the proton:

$$g_1(x) = \frac{1}{2}\sum_i e_i^2 \left[q_i^{(+)}(x) - q_i^{(-)}(x)\right]. \tag{5}$$

Here $q_i^+(x)$ $[q_i^-(x)]$ is the distribution function of quark i with spin parallel [antiparallel] to that of the proton at that value of x.

We can also write

$$\int g_1^p(x)\,dx = \tfrac{1}{2}\left(\tfrac{4}{9}\Delta u + \tfrac{1}{9}\Delta d + \tfrac{1}{9}\Delta s\right), \tag{6}$$

with

$$\Delta q_i = \int dx\left(q_i^{(+)} + \bar{q}_i^{(+)} - q_i^{(-)} - \bar{q}_i^{(-)}\right) + \mathcal{O}(\alpha_s/\pi) \tag{7}$$

and

$$\Delta q s_\mu = \langle p, s|\bar{q}\gamma_\mu\gamma_5 q|p, s\rangle, \tag{8}$$

where s is the spin of the proton.

Experimentally [5], it is found that for the proton

$$\int g_1^p\, dx = 0.126 \pm 0.01 \pm 0.015, \tag{9}$$

whereas theory, *i.e.*, the Ellis-Jaffe sum rule [6] gives

$$\int g_1^p\, dx = 0.175 \pm .018. \tag{10}$$

The neutron contribution $g_1^n dx$ is expected to be small, and the Bjorken sum rule [7] gives

$$\int g_1^p\, dx - \int g_1^n\, dx = \tfrac{1}{6} g_{\mathrm{A}} \left(1 - \frac{\alpha_s}{\pi}\right) = 0.191 \pm 0.02. \tag{11}$$

In this sum rule, the strangeness contribution washes out, since it should be identical for the proton and neutron. If $\int g_1^n\, dx$ is small, the EMC experiment indicates that the Bjorken sum rule is violated and that the violation is not due to the strangeness axial vector matrix element. In either case, it seems that we do not really understand the structure of the nucleon.

Theoretically, we know that [8]

$$\begin{aligned} \Delta u - \Delta d &= F + D = 2\langle p | J_{Az}^{(3)} | p \rangle = g_{\mathrm{A}} = 1.26, \\ \Delta u + \Delta d - 2\Delta s &= 3F - D = 2\sqrt{3}\langle p | J_{Az}^{(8)} | p \rangle, \\ \Delta u + \Delta d + 2\Delta s &= 2\sqrt{3/2}\langle p | J_{Az}^{(0)} | p \rangle, \end{aligned} \tag{12}$$

where J_{Az} is the axial vector current in the z-direction and the superscripts are SU(3) indices. If the results of the EMC experiments are combined with baryon decay data, we obtain

$$\begin{aligned} \Delta u &= 0.78 \pm .07, \\ \Delta d &= -0.48 \pm .07, \\ \Delta s &= -0.19 \pm .07, \\ \sum_i \Delta q_i &= 0.11 \pm 0.23. \end{aligned} \tag{13}$$

Equation (13) shows that the quarks carry almost none of the spin of the proton. Since we know that

$$S_z^q + S_z^g + L_z = \tfrac{1}{2} \sum_i \Delta q_i + \Delta g + L_z = \tfrac{1}{2}, \tag{14}$$

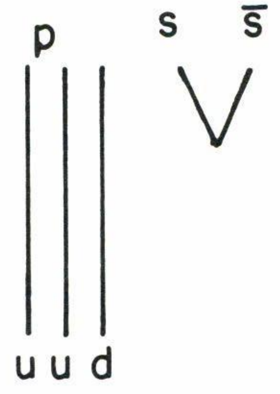

FIGURE 1. A disconnected diagram for ϕ production from a nucleon.

the spin of the proton appears to originate primarily from gluons (Δg) and orbital angular momentum (L_z). In the non-relativistic quark model $\Delta s = 0$, $\Delta u = 4/3$, $\Delta d = -1/3$, and all the spin originates from the spin of the quarks. Again, we conclude that the quark-gluon structure of the proton is not understood. the experiments outlined in the next section are intended to provide more information.

1.3. OZI rule violation

Another indication that there may be non-vanishing strangeness matrix elements in the nucleon is the production of ϕ mesons in $\bar{p}p$ annihilation. Such production should be severely inhibited by the OZI rule, which states that disconnected diagrams (*e.g.*, Fig. 1) are severely ($\lesssim 10^{-2}$) inhibited. Experimentally it is found that [9]

$$\frac{\sigma(\bar{p}p \to \phi\pi^+\pi^-)}{\sigma(\bar{p}p \to \omega\pi^+\pi^-)} \approx 2 \times 10^{-2}, \tag{15a}$$

and

$$\frac{\sigma(\bar{p}n \to \phi\pi^-)}{\sigma(\bar{p}n \to \omega\pi^-)} \approx 0.13. \tag{15b}$$

Both ratios are an order of magnitude larger than anticipated from the OZI rule [10], but could be "explained" with a scalar matrix element $\langle N|\bar{s}s|N\rangle$ of the order of 10–20% of $\langle\bar{N}|\bar{u}u + \bar{d}d + \bar{s}s|N\rangle$.

1.4. Elastic neutrino proton scattering

As a final indication of non-vanishing strangeness matrix elements in the nucleon, consider elastic neutrino scattering. A Brookhaven measurement of the elastic ν and $\bar{\nu}$ scattering cross section on protons as a function of Q^2 is shown in Fig. 2 [11]. the measurement by Ahrens *et al.* [11] shows that the Q^2 dependence is consistent with a dipole form factor with a mass, $M_A \approx 1.03$ GeV. (However, charged current cross sections lead to

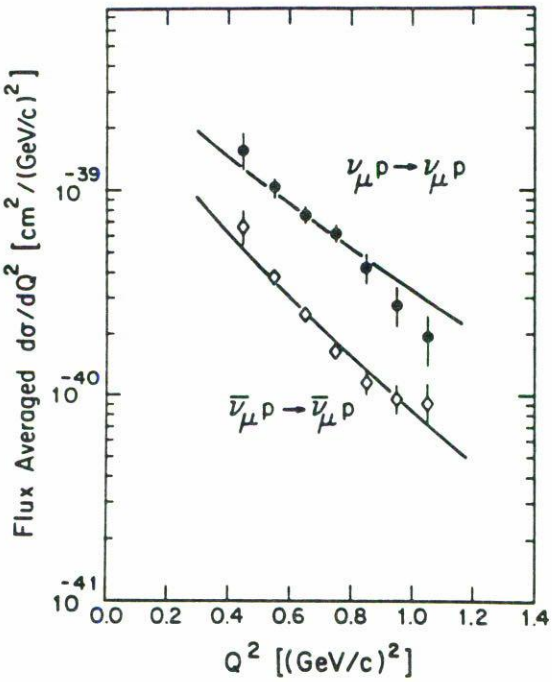

FIGURE 2. Neutrino and antineutrino elastic scattering cross sections from protons as a function of Q^2. Taken from Ref. [11].

$M_A \approx 1.09$ GeV.) When extrapolated to $Q^2 = 0$, there is disagreement with the standard model coupling constants. Agreement can be reached if a strange (isoscalar or SU(3) scalar) axial vector coupling constant [12],

$$g_A^s \approx -0.15 \pm 0.08, \tag{16}$$

is introduced. This coupling measures $\langle N|\bar{s}\gamma^\mu\gamma^5 s|N\rangle$, and would be zero if this matrix element vanishes.

There are problems with all four of these experiments. For instance, in the elastic neutrino scattering on protons, the form factor is not known and the error in the determination of M_A may be larger than stated; this would lead to a larger error in the determination of g_A^s. G. Garvey *et al.* have reanalyzed this experiment [13]. Nevertheless, these four experiments all provide an indication that strangeness is present in the nucleon to a remarkably large degree. Some strangeness is to be expected, since $p \to \Lambda^0 K^+ \to p$, but, as we will show later, this results in only a small % of strangeness. The experiments also show that we do not fully understand the substructure of the nucleon. What other experiments can be done to elucidate it?

2. EXPERIMENTS TO MEASURE STRANGENESS IN THE NUCLEON

In addition to the four experiments that have already been carried out, new ones are feasible. I will focus on measurements of new, unconstrained, and unknown form factors of the proton which should exist if strangeness is present in the nucleon. These elastic form factors can be written as

$$\langle N|\bar{s}\gamma^{\mu}s|N\rangle \longrightarrow F_2^s(q^2)\bar{U}_N\sigma^{\mu\nu}\frac{q_\nu}{2M}U_N \tag{17a}$$

and

$$\langle N|\bar{s}\gamma^{\mu}\gamma^5 s|N\rangle \longrightarrow F_{\rm A}^s(q^2)\bar{U}_N\gamma^{\mu}\gamma^5 U_N \tag{17b}$$

with $F_{\rm A}^s(0) = -g_{\rm A}^s$ and M the nucleon mass. Let me briefly remind you of the definition of these form factors. In SU(2) the standard model predicts

$$J_\mu^\gamma(N) = \bar{U}(p')\left[\gamma_\mu F_1^\gamma + i\sigma_{\mu\nu}\frac{q^\nu}{2M}F_2^\gamma\right]U(p), \tag{18a}$$

$$J_\mu^Z(N) = \bar{U}(p')\left[\gamma_\mu F_1^Z + i\sigma_{\mu\nu}\frac{q^\nu}{2M}F_2^Z + \gamma_\mu\gamma_5 F_{\rm A}\right]U(p), \tag{18b}$$

with

$$F_1^\gamma = \tfrac{1}{2}\left[F_1^{\rm IS}(Q^2) + \tau_3 F_1^{\rm IV}(Q^2)\right] \underset{Q^2\to 0}{\longrightarrow} \begin{pmatrix} 1 \\ 0 \end{pmatrix} \begin{matrix} \text{for the proton} \\ \text{for the neutron,} \end{matrix} \tag{19a}$$

$$\begin{aligned} F_2^\gamma &= \tfrac{1}{2}\left[(\kappa_p + \kappa_n)F_2^{\rm IS}(Q^2) + \tau_3(\kappa_p - \kappa_n)F_2^{\rm IV}(Q^2)\right] \\ &\underset{Q^2\to 0}{\longrightarrow} \begin{pmatrix} \kappa_p \\ \kappa_n \end{pmatrix} \begin{matrix} \text{for the proton} \\ \text{for the neutron,} \end{matrix} \end{aligned} \tag{19b}$$

$$\begin{aligned} F_1^Z &= \tfrac{1}{4}\left[-2\sin^2\theta_{\rm W}F_1^{\rm IS}(Q^2) + (1 - 2\sin^2\theta_{\rm W})F_1^{\rm IV}(Q^2)\tau_3\right] \\ &\underset{Q^2\to 0}{\longrightarrow} \begin{pmatrix} \frac{1}{4}[1 - 4\sin^2\theta_{\rm W}] \\ -\frac{1}{4} \end{pmatrix} \begin{matrix} \text{for the proton} \\ \text{for the neutron,} \end{matrix} \end{aligned} \tag{19c}$$

$$\begin{aligned} F_2^Z &= \tfrac{1}{4}\left[-2\sin^2\theta_{\rm W}(\kappa_p + \kappa_n)F_2^{\rm IS}(Q^2)\right. \\ &\quad \left. + (1 - 2\sin^2\theta_{\rm W})\tau_3(\kappa_p - \kappa_n)F_2^{\rm IV}(Q^2)\right] \\ &\underset{Q^2\to 0}{\longrightarrow} \begin{pmatrix} \frac{1}{4}[(1 - 4\sin^2\theta_{\rm W})\kappa_p - \kappa_n)] \\ \frac{1}{4}[-\kappa_p + (1 - 4\sin^2\theta_{\rm W})\kappa_n] \end{pmatrix} \begin{matrix} \text{for the proton} \\ \text{for the neutron,} \end{matrix} \end{aligned} \tag{19d}$$

$$\begin{aligned} F_{\rm A} &= \tfrac{1}{4}\left[g_{\rm A}^{\rm IS}F_{\rm A}^{\rm IS}(Q^2) + F_{\rm A}^{\rm IV}(Q^2)\tau_3 g_{\rm A}\right] \\ &\underset{Q^2\to 0}{\longrightarrow} \begin{pmatrix} \frac{1}{4}g_{\rm A} \\ -\frac{1}{4}g_{\rm A} \end{pmatrix} \approx \begin{pmatrix} -\frac{1.26}{4} \\ \frac{1.26}{4} \end{pmatrix}. \end{aligned} \tag{19e}$$

Here $F_i^\gamma(F_i^Z, F_A)$ are electromagnetic and weak form factors, normalized to unity at $Q^2 = 0$ and θ_W is the Weinberg angle; g_A^{IS} is an isoscalar coupling, which is zero in the standard model. If s quarks are present, we have to use SU(3) notation and can write

$$F_1^\gamma = \tfrac{1}{2}\left[F_1^{(8)}(Q^2) + \tau_3 F_1^{(3)}(Q^2)\right] \xrightarrow[Q^2\to 0]{} \begin{pmatrix} 1 \\ 0 \end{pmatrix} \begin{matrix}\text{for the proton} \\ \text{for the neutron,}\end{matrix} \tag{20a}$$

$$F_2^\gamma = \tfrac{1}{2}\left[(\kappa_p + \kappa_n)F_2^{(8)}(Q^2) + \tau_3(\kappa_p - \kappa_n)F_2^{(3)}(Q^2)\right] \xrightarrow[Q^2\to 0]{} \begin{pmatrix} \kappa_p \\ \kappa_n \end{pmatrix}, \tag{20b}$$

$$F_1^Z = \tfrac{1}{4}\left[-F_1^{(0)}(Q^2) + \tau_3 y F_1^{(3)}(Q^2) + y F_1^{(8)}(Q^2)\right] \xrightarrow[Q^2\to 0]{} \begin{pmatrix} \frac{1}{4}[1 - 4\sin^2\theta_W] \\ -\frac{1}{4} \end{pmatrix}, \tag{20c}$$

$$F_2^Z = \tfrac{1}{4}\left[-g_2^{(0)}F_2^{(0)}(Q^2) + \tau_3 y(\kappa_p - \kappa_n)F_2^{(3)}(Q^2) + y(\kappa_p + \kappa_n)F_2^{(8)}(Q^2)\right] \xrightarrow[Q^2\to 0]{} \begin{pmatrix} -g_2^{(0)} + 2y\kappa_p \\ -g_2^{(0)} + 2y\kappa_n \end{pmatrix}, \tag{20d}$$

$$F_A = \tfrac{1}{4}\left[-g_A^{(0)}F_A^{(0)}(Q^2) + 2g_A\tau_3 F_A^{(3)}(Q^2) + (6F - 2D)F_A^{(8)}(Q^2)\right]. \tag{20e}$$

Here $y = (1 - 2\sin^2\theta_W)$, $g_2^{(0)} = (\kappa_p + \kappa_n) + \kappa^s$, $(6F - 2D) \approx 1.1$, with F and D the fraction that are odd and even under SU(3); $6F - 2D \approx 1.1$, and $g_A \approx -1.26$. The superscripts are SU(2) indices. If strange quarks are present in the nucleon, then the Q^2 dependence of F_1^Z and F_1^γ need not be the same, and there are two new couplings and form factors, namely the SU(3) scalars, $g_2^{(0)}F_2^{(0)}(Q^2)$ and $g_A^{(0)}F_A^{(0)}(Q^2)$. These couplings and form factors are unknown and unconstrained, but we have defined $F_A^s(0) = -g_A^{(0)}$. In addition, we have $F_i^{IS} = F_i^{(0)} + F_i^{(8)}$.

The experiments below are aimed primarily at measuring $g_A^{(0)}F_A^{(0)}(Q^2)$ and $g_2^{(0)}F_2^{(0)}(Q^2)$.

2.1. Parity-nonconserving asymmetry in elastic polarized electron proton scattering

It was shown by Beck, McKeown [14], and others that the scattering of longitudinally polarized electrons on protons allows a determination of $g_2^{(0)}F_2^{(0)}$. The parity-nonconserving asymmetry can be written as

$$a = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L} = -\frac{GQ^2}{\sqrt{2}\,\pi\alpha}\Big\{\left[2\xi\tan^2\tfrac{\theta}{2}(F_1^\gamma + F_2^\gamma)(F_1^Z + F_2^Z) + F_1^\gamma F_2^Z + F_2^\gamma F_2^Z\xi\right]$$

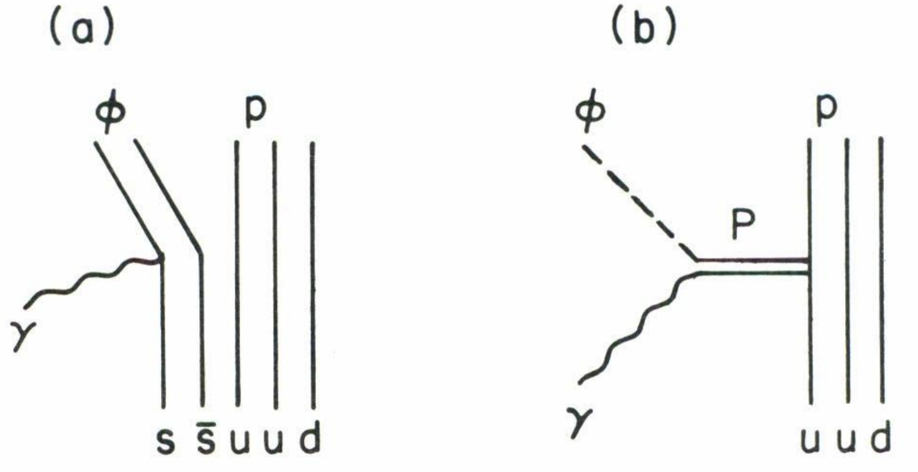

FIGURE 3. (a) Knock-out electro-production of ϕ mesons; (b) VMD electro-production of ϕ mesons.

$$- \frac{E+E'}{2M} \tan^2 \tfrac{\theta}{2} (1 - 4\sin^2\theta_W) F_A (F_1^\gamma + F_2^\gamma) \Big\}$$

$$\times \left\{ (F_1^\gamma)^2 + \xi (F_2^\gamma)^2 + 2\xi \tan^2 \tfrac{\theta}{2} (F_1^\gamma + F_2^\gamma)^2 \right\}^{-1}, \tag{21}$$

where E (E') is the initial (final) electron energy, θ is the scattering angle, and $\xi \equiv Q^2/4M^2$. The last term in Eq. (21) is small because $(1 - 4\sin^2\theta_W) \approx 0.1$, and the second one is small at back angles, where the first term dominates. Thus, at back angles the asymmetry is sensitive to F_2^Z, and allows a determination of $F_2^{(0)}$ and therefore F_2^s. This experiments is being undertaken at MIT and is planned at CEBAF.

2.2. Electro ϕ production

Another experiment that is sensitive to strangeness vector matrix element F_2^s is the electro-production of ϕ mesons. Because of the OZI rule, this production is inhibited unless strangeness is present, Fig. 3a [15]. However, we found that it is difficult to differentiate between this process and the vector meson dominance (VMD) contribution, shown in Fig. 3b. Present data [16] agrees with VMD to within the experimental error of $\sim 10\%$. A clean differentiation between the two processes may require polarization data [15].

2.3. Parity-nonconserving asymmetry in electron-deuteron scattering

The parity non-conserving asymmetry in polarized electron scattering from deuterium could be used to measure $g_A^{(0)} F_A^{(0)}$ [17]. Although the asymmetry is reduced by $(1 - 4\sin^2\theta_W)$, there is no isovector competition. The asymmetry for polarized deuterons is cleaner, but much more difficult experimentally.

2.4. νp elastic scattering

The advantage of measuring cross sections in neutrino scattering over parity non-conserving electron scattering is that there is no reduction of $(1-4\sin^2\theta_W) \approx 0.1$ due to the vector current of the electron. Lower energy, ($\langle E\rangle \sim 500$ MeV) νp elastic scattering would allow the extraction of $g_A^{(0)}$ more clearly than the higher energy experiment of Ahrens *et al.* [11] because the former is much less sensitive to the Q^2 dependence of the axial vector form factor. Such an experiment is being undertaken by G. Garvey at Los Alamos [18].

2.5. Inelastic ν ^{12}C scattering

The excitation of the 1^+, isospin 0, excited state at 12.71 MeV in ^{12}C is particularly sensitive to $g_A^{(0)}F_A^{(0)}$ [19]. However, there is a background due to magnetic scattering and mixing of the $I=1$, $J^p=1^+$ state at 15.11 MeV with the $I=0$, 12.11 MeV state [19].

2.6. Quasi-elastic ν scattering on ^{12}C

The ratio

$$\nu\frac{\sigma(\nu+{}^{12}\mathrm{C}\to\nu+p+\cdots)}{\sigma(\nu+{}^{12}\mathrm{C}\to\nu+n+\cdots)} \tag{22}$$

is sensitive to $g_A^{(0)}F_A^{(0)}$ [20], due to an interference of the axial and vector currents. A measurement of this ratio has been proposed by Garvey [20].

2.7. ν and $\bar\nu$ elastic scattering on ^2H

In Seattle, we have proposed [21] the measurement of the ratio R

$$R=\frac{\sigma(\nu d\to\nu d)-\sigma(\bar\nu d\to\bar\nu d)}{\sigma(\nu d\to\nu d)+\sigma(\bar\nu d+\bar\nu d)}. \tag{23}$$

It is necessary to use an isospin $=0$, spin $\neq 0$ target. The numerator of this ratio is proportional to $v_\mu a_\nu V^\mu A^\nu$, where $v(a)$ and $V(A)$ are the vector (axial vector) currents of the neutrino (v,a) and deuteron (V,A), respectively. Although this is a difficult experiment, it has the advantage of being a null experiment. Because the deuteron has isospin $I=0$, the numerator vanishes unless $R\propto\langle d|\bar s\gamma^\nu\gamma^5 s|d\rangle\propto g_A^{(0)}F_A^{(0)}\neq 0$; this comes about because $g_A^{\mathrm{IS}}=-g_A^s=g_A^{(0)}$. Furthermore the ratio R can be sizeable even if $g_A^{(0)}$ is small. We have calculated R for neutrino energies up to 2 GeV by several methods:

a) By means of a multipole expansion and extended Siegert theorem for $E_\nu \lesssim 150$ MeV.

b) In the Breit frame by means of a covariant formalism for nonrelativistic deuterons for 100 MeV $\lesssim E_\nu \lesssim 1$ GeV.

c) By means of a light cone impulse approximation for 500 MeV $\lesssim E_\nu \lesssim 2$ GeV.

Here, I will illustrate the results for the covariant method, where form factors are evaluated in the Breit frame with a non-relativistic reduction of nuclear currents for nucleons moving in the Paris potential [22].

Because the isoscalar axial vector from factor $F_A^{(0)}$ is not known, we assume $F_A^{(0)} = F_A^{(3)}$, the isovector one; it has been measured [11] to be $(1 + Q^2/M_A^2)^{-2}$ with $M_A \approx 1.03$ GeV. We can write the deuteron cross sections as [21]

$$\frac{d\sigma}{dQ^2}\begin{pmatrix}\nu d\\ \bar{\nu} d\end{pmatrix} = \frac{G_F^2}{2\pi}\eta\left[2W_1 \sin^2\tfrac{\theta}{2} + W_2\cos^2\tfrac{\theta^2}{2} \mp \frac{2}{M}(E_\nu + E'_\nu)W_8 \sin^2\tfrac{\theta}{2}\right], \tag{24}$$

where

$$W_1 = \frac{Q^2}{6M^2}\left(1 + \frac{Q^2}{4M^2}\right)G_M^2 + \frac{2}{3}\left(1 + \frac{Q^2}{4M}\right)F_A^{(0)^2} g_A^{(0)^2}, \tag{25a}$$

$$W_2 = \left[G_c^2 + \frac{Q^2}{6M^2}G_M^2 + \frac{Q^4}{18M^4}G_Q^2 + \tfrac{2}{3}(1+\xi)G_A^2\right], \tag{25b}$$

$$W_8 = \tfrac{2}{3}(1+\xi)G_M G_A. \tag{25c}$$

Here G_c, G_Q, G_M, G_A are the Coulomb, quadrupole, magnetic and axial deuteron form factors, respectively. The difference $\frac{d\sigma}{dQ^2}(\nu d \to \nu d) - \frac{d\sigma}{dQ^2}(\bar{\nu} d \to \bar{\nu} d)$ vanishes if G_A (or $g_A^{(0)} F_A^{(0)}) = 0$; the ratio R is proportional to $g_A^{(0)}$ for $Q^2 \leq 1(GeV/c)^2$, away from the zeros of $G_A(Q^2)$, and if R is not too close to unity. Figure 4 presents the cross section for ν and $\bar{\nu}$ scattering on d. Figure 5 shows the ratio R for deuterons of 500 MeV as a function of Q^2 for $g_A^{(0)} = 0.1$ and 0.2 with $F_2^{(0)} = 0$. Figure 6 shows the ratio R for $E_\nu = 2$ GeV and $g_A^{(0)} = 0.1$ and 0.2; the zero is caused by a vanishing form factor and makes it clear that lower neutrino energies are preferred. Figure 7 presents R for $E_\nu = 500$ MeV, $g_A^{(0)} = 0.2$ and $F_2^{(0)} = 0$, and ± 0.2. Finally, Figure 8 should help experimental physicists to choose the best neutrino energy: Large Q^2 makes it easier to detect recoil deuterons, but at the cost of a smaller cross section, for neutrinos of 500 MeV the long-and-short dashed curves correspond to cross section of 10^{-42} and 10^{-41} cm^2/GeV^2, respectively. If it is desired to have a minimum cross section of one of these numbers and a ratio $R \geq 0.25$, then the two shaded regions show the allowed range of scattering angle θ.

3. Conclusions

There are a variety of new experiments that can be carried out to determine two totally unknown constants ($g_A^{(0)}$, $F_2^{(0)}(0)$) and nucleon structure functions. The experiments are difficult, but feasible, and some are being undertaken.

It is important to carry out new measurements of the strangeness matrix elements in the nucleon, so that we can gain a better understanding of its internal structure.

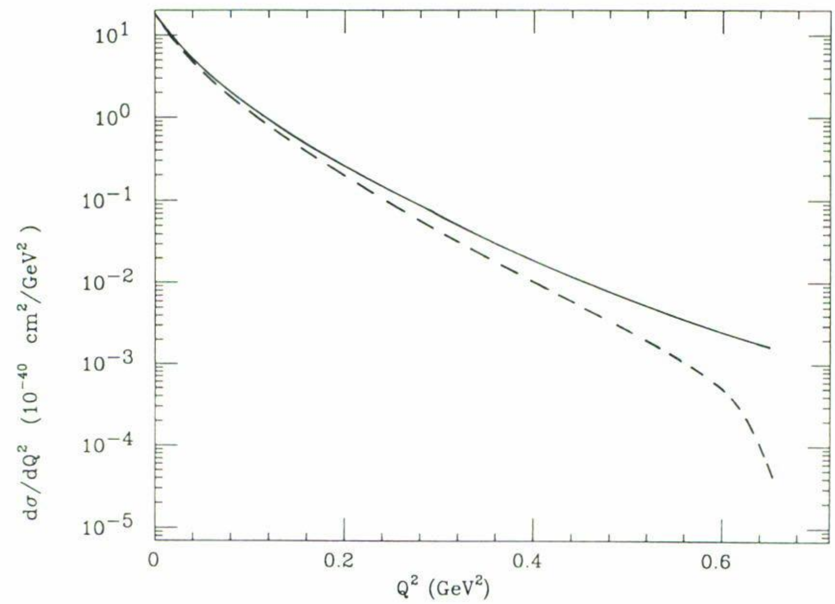

FIGURE 4. Cross sections for νd (solid) and $\bar{\nu} d$ (dashed) elastic scattering as a function of Q^2.

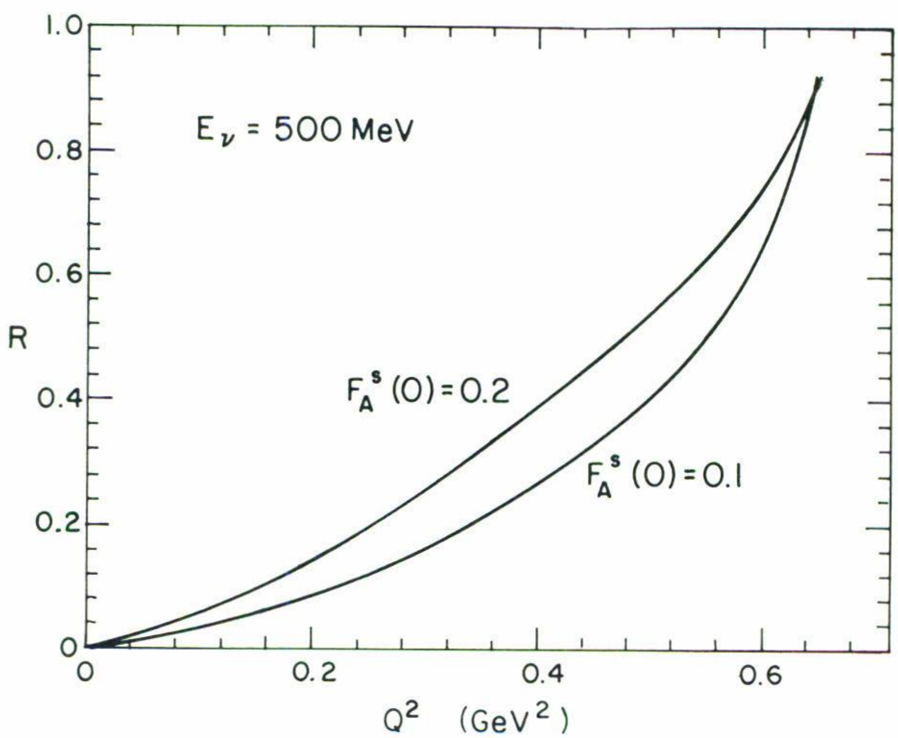

FIGURE 5. R for 500 MeV neutrinos as a function of Q^2 for $-g_A^{(0)} \equiv F_A^s(0) = 0.1$ and 0.2 with $F_2^{(0)} = 0$.

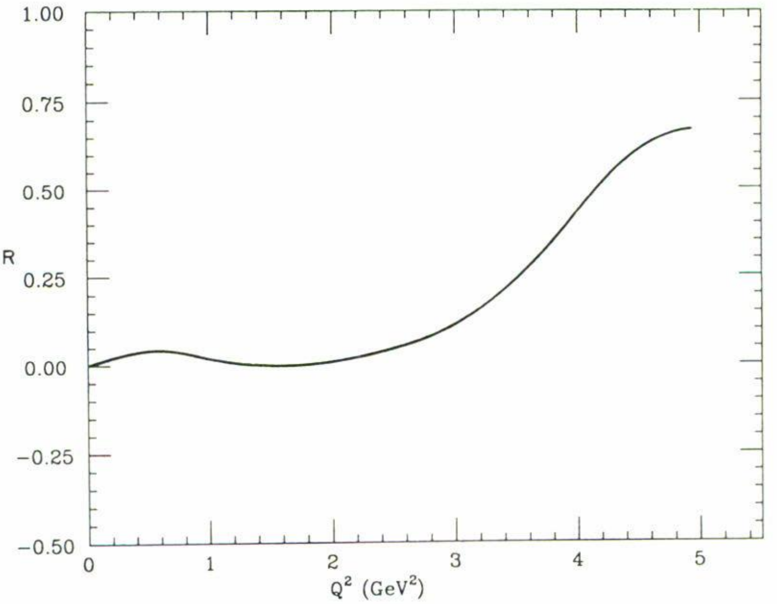

FIGURE 6. Same as Fig. 5 for 2 GeV neutrinos, but only for $g_A^{(0)} = -0.1$.

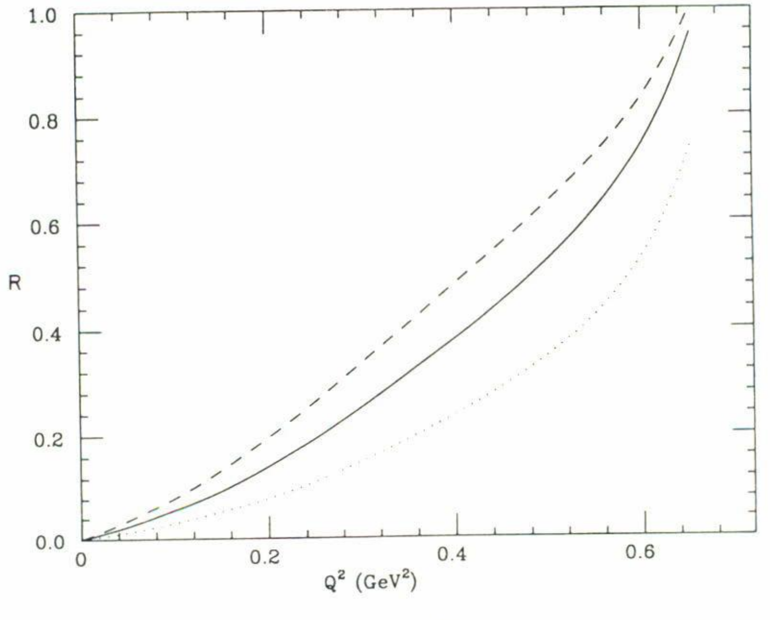

FIGURE 7. Same as Fig. 5, but for $g_A^{(0)} = 0.2$ and $F_2^{(0)} = 0$, (solid) and 0.2 (dashed) and −0.2 (dotted).

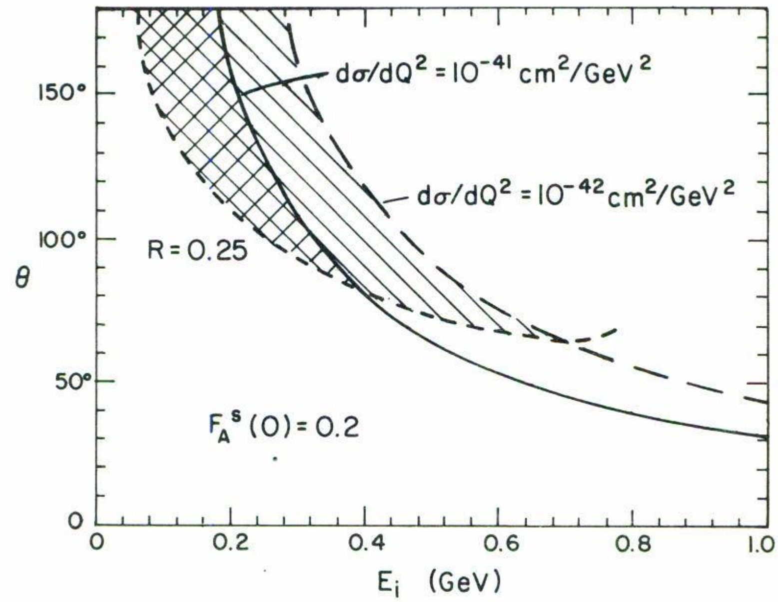

FIGURE 8. Experimental limits on scattering angle (θ) as a function of neutrino energy for $F_A^s(0) = -g_A^{(0)} = 0.2$, and $R = 0.25$ as well as cross section of 10^{-41} and 10^{-42} cm^2/GeV^2.

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